# Robotic Outposts as Precursors to a Manned Mars Habitat


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**Abstract**. A cost effective approach for the deployment of manned habitats on planetary surfaces is the use of robotic precursor missions for such tasks as the deployment and servicing of power systems and ISRU generators, construction of beaconed roadways, and the site preparation and deployment of manned habitat modules. Limitations in the lifetime, dexterous manipulation capabilities, control system architectures, mobility, and the overall degree of autonomy of the current generation of planetary rovers such as Sojourner will have to be addressed before such a long term effort can be undertaken. Ongoing work in the Surface Systems Thrust Area under NASA's Cross Enterprise Technology Development Program (CETDP) in the area of robotic outposts is enabling many of the technology developments necessary for such an ambitious undertaking. This effort includes a strong cross section of University and NASA Center partners. The program includes the development of control architectures, ISRU systems, and new mobility designs for a sustained long term presence on planetary surfaces. This paper reviews some recent results from the JPL tasks under the Program and provides a roadmap for integration into robotic precursor missions in the 2010-2015 timeframe.


## INTRODUCTION

Infrastructure needs for robotic outposts must also include their eventual integration into hybrid human/robot systems. As such, the design of habitat elements and control interactions should be tailored with this in mind. This is not to say that only humanoid robot designs can be used, but that habitat structures for example are constructed for robotic access and manipulation prior to human arrival. An illustration of a possible precursor robotic colony is shown in Figure 1. There are many ongoing tasks in the figure, that are probably best done by heterogeneous robots.

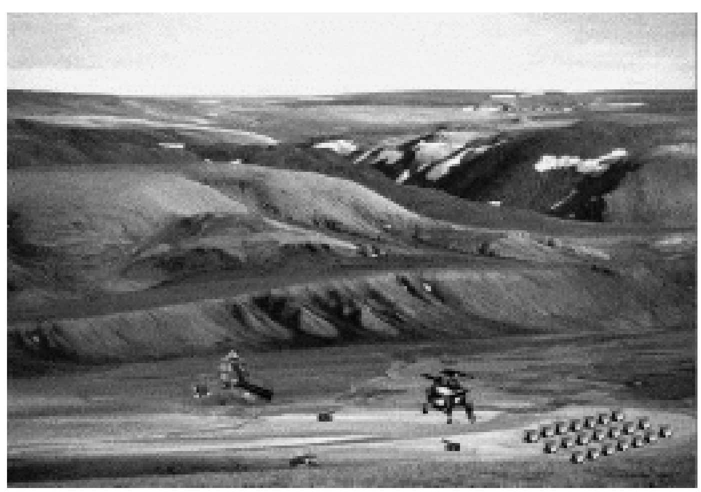


FIGURE 1. Mars Habitat Prior to the Arrival of the Manned Missions. Site clearing is ongoing using small autonomous dozers. ISRU plant and habitat are in place and the solar PV tent array has been partially deployed

There are a number of robotics requirements that will need to be addressed before the arrival of the manned missions. These include both the precursor tasks as well as the needs for a sustained robotic presence on the planetary surface. Among the baseline robotics requirements (not necessarily exhaustive or in order of importance):

- Load transportation and handling
- Solar power system deployment
- Terrain conditioning and site preparation
- Infrastructure servicing and repair
- Object manipulation and handling
- ISRU plant deployment
- Internal habitat servicing

The current work at JPL is concentrating on the first two points, since power system deployment is the single most enabling task for a robotic precursor mission.

## LOAD TRANSPORTATION AND HANDLING

Use of a centralized supply cache for a planetary surface construction task simplifies the control algorithms, since the cache and deployment zones can be beaconed thus minimizing the need for visual autonomy. The tradeoff is the requirement for longer transport capabilities. In addition, for the transport of extended structural elements, single robot systems may not be capable of carrying the containers. The added complexity of multirobot control is offset by the reduction in the load carrying needs for each robot. Mechanical work requirements for an illustrative outpost scenario derived from the Mars Reference Mission (Hoffman and Kaplan, 1997; Drake, 1998) are shown in TABLE 1.

TABLE 1. Mass/Work Assessment for Robotic Precursor Tasks Related to a Manned Mars Habitat.

| Element of Sub-Assembly | Mass (kg) | Horizontal Load Travel (m) | Vertical Load Travel (m) | Total Mechanical Work (N-m) |
|---|---|---|---|---|
| Power System | 3,500 | 200 | 5 | 630,000 |
| Habitat | 1,000 | 100 | 5 | 100,000 |
| Science Station | 500 | 100 | 5 | 50,000 |
| Communication Station | 500 | 100 | 5 | 50,000 |
| Landing Pad Infrastructure | 1,000 | 100 | 5 | 100,000 |
| Other | 2,000 | 100 | 5 | 200,000 |
| Total | 8,500 | 700 | 30 | 1,130,000 |

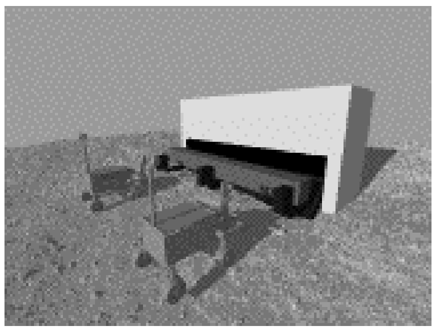
From this table it is possible to conclude that the robotic transportation requirements implied by the Mars Reference Mission (Hoffman and Kaplan, 1997; Drake, 1998) would require that the robotic capabilities in load transportation be increased over two orders of magnitude from those achieved in the Sojourner mission and a least an order of magnitude over that likely to be achieved for the rover in the Athena 2003 mission. We have assumed a coefficient of rolling friction for the robots of 0.21. The "Other" category in TABLE 1 represents all of the tasks that are not directly attributable to a specific construction project (e.g. general site cleanup). The power system deployment requirements appear to be by far the most challenging.

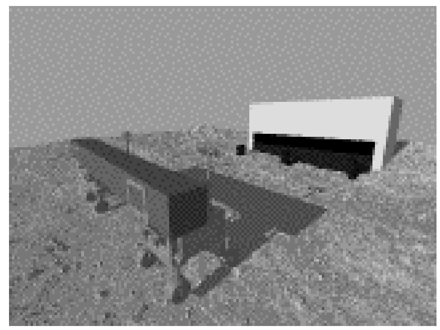
## SOLAR POWER SYSTEM DEPLOYMENT

The power needs for human surface operations are substantial. Power source requirements on the order of (100+ kWe) are anticipated. Of this, about 30 kW are needed for habitation, 30-60 kW are needed for regenerative life support, and 50 kW are needed for in-situ resource utilization. A power generator of about 12-14 tonnes, or multiple power generators of about 5 tonnes each, may be needed. Alternatively, solar power arrays of about 5000 square meters minimum are needed with present technology. The advantages of the solar PV tent arrays include modularity, relatively low overall mass (3.5 tonne), and political/environmental viability.

Assuming as an example a large, modular PV tent option for the power system, the required operations are as follows. The individual tent boxes must be off-loaded from the container storage unit (CSU) and moved to a cleared area 100 to 200 meters from the base. The PV tents then have to be deployed. This scenario is shown in FIGURE 2. High voltage (2-5 kV) distribution lines as well as monitoring and control lines must be set up.

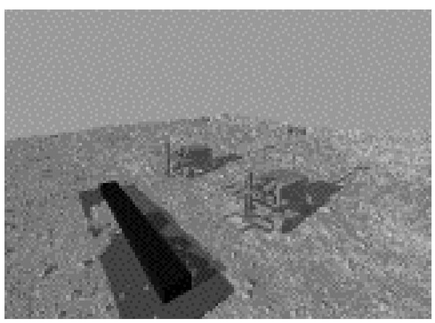
We are currently investigating under CETDP funding the robotic needs for the deployment of a modular solar PV tent array such as that specified by Colozza (1991). Colozza's study demonstrated that a nearly constant power

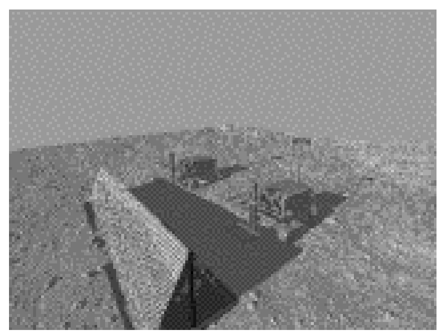




(a) Unload Container from Container Storage Unit (CSU).

(b) Traverse to Deployment Site.





(c ) Position and Open Container.

(d) Deploy PV Tent.

FIGURE 2. Four Step Sequence for a PV Tent Array Deployment. PV Tent Storage Container is 5 m in Length and is Not Well Handled by a Single Robot.

profile can be realized by a tent array using a blanket of standard silicon PV cells. In addition, atmospheric dust deposition is minimized due to the steep angle of repose (60 degrees) of the PV blankets. The study also included an examination of the relevant wind force upon the array. Such a PV tent array would be difficult to deploy using a solitary robot, since the modules are 5 meters long and would represent a considerable challenge for precision placement. Two cooperating robots can perform the task using the sequence of steps shown in FIGURE 2. These steps were decided upon keeping in mind the mass and power constraints consistent for a mobile robotic platform on the Martian surface.

The main robotics requirements for this task include coordinated grasping and navigation over open terrain by two or more cooperating robots. Navigation over unconstrained terrain will prove to be a significant challenge. In addition, there must be accurate localization of the robots as the PV tent containers are unloaded from the CSU and delivered to the site, since damage to the solar blankets would otherwise occur. We are currently investigating the use of fused visual and sun sensors for this task. A control architecture called CAMPOUT (Control Architecture for Multi-robot Planetary Outposts) shown in FIGURE 3 is being developed based on a three layer structure and behavior based algorithms (Pirjanian, 2000; Pirjanian, et al, 2000). We have previously investigated the use of behavior-based control for robotic outposts using simulation (Huntsberger, Mataric, and Pirjanian, 1999).

CAMPOUT is basically a three-layer architecture, which may be a derived from the types of environments in which planetary rover systems are expected to operate and survive (Gat, 1998). A long duration mission such as a robot outpost on a planetary surface has a wide range of needs from the low level reactive components for local navigation and manipulator control to the higher level planning for large-scale construction tasks. The three-layer architecture spans these requirements through drivers directly tied to the actuators receiving commands from a behavior-based control hierarchy that is driven by a higher task planning layer.

Currently, CAMPOUT provides the following facilities for behavior representation, behavior generation, behavior coordination, and communications infrastructure for distributed robot coordination:

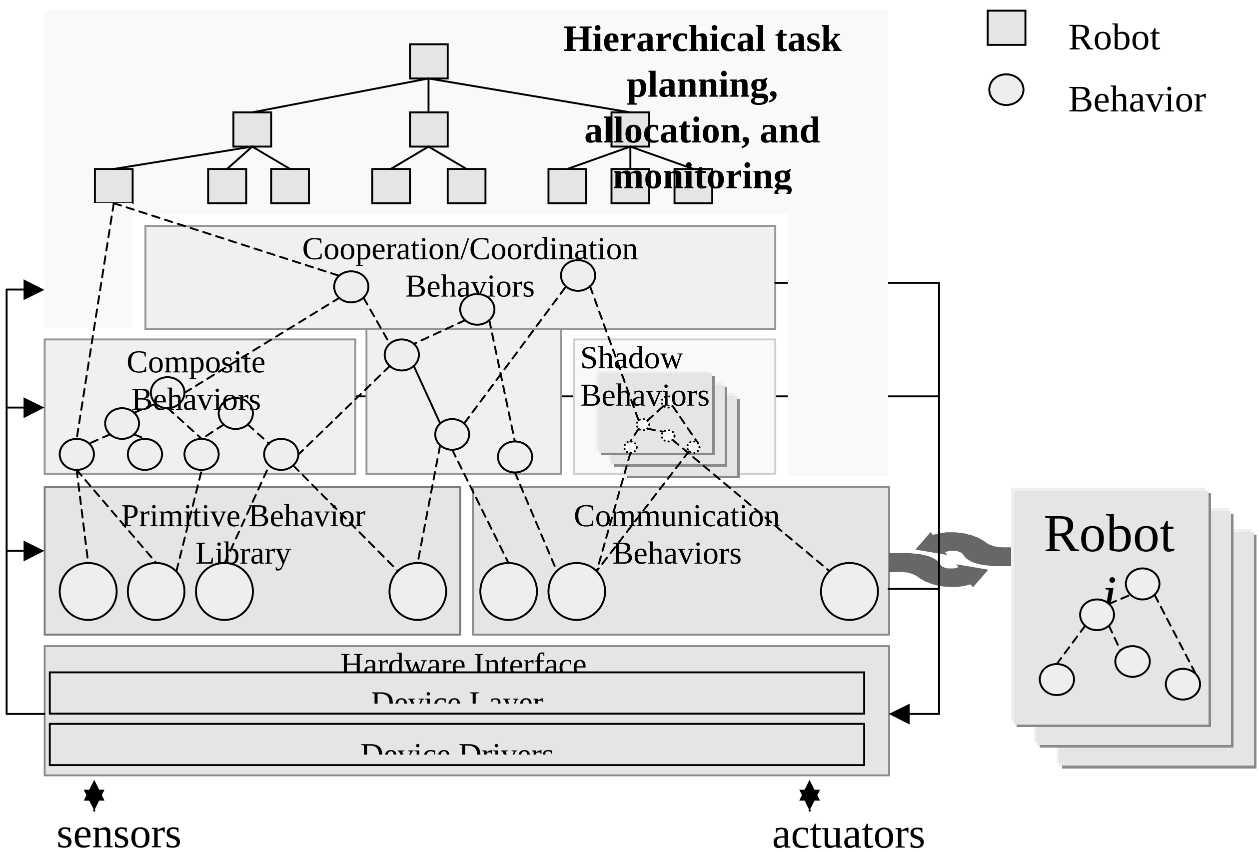



FIGURE 3. Logical Block Diagram of the Control Architecture for Multi-robot Planetary Outposts, its Components, Interaction between Components, and Interfaces.

- **Behavior representation:** a set of abstract data types (known as objective functions) and related operations to describe the output of a general behavior as a multivalued preference.
- **Behavior prototyping toolkit:** provides a set of tools for rapid-prototyping of primitive as well as composite behaviors, i.e., facilities that can be used to easily develop behaviors.
- **Behavior coordination mechanisms:** that provide a repertoire of mechanisms that can be used to coordinate the activities of lower-level behaviors to form higher-level composite behaviors.
- **Communications infrastructure:** provides a set of tools and functions for interconnecting a set of robots and/or behaviors for sharing resources (e.g., sensors or actuators), exchanging information (e.g., state, percepts), synchronization, rendezvous etc.

CAMPOUT uses behavior fusion of primitive (single agent) and communication behaviors to build group (composite) behaviors in the middle layer of the architecture (Pirjanian, 2000). In this way, a set of primitive behaviors can be used as a library to implement a general class of coordinated control systems within a single architecture. In addition, these middle layer behavior sets are decoupled from specific device drivers at the hardware level.

## EXPERIMENTAL STUDIES

(a) Rovers in a Column Formation (b) Closeup of Instrumented Gimbal and Container (c) Rovers in a Row Formation

FIGURE 4. Extended Container Transport by Two Rovers in the Arroyo Seco at JPL.

Our experimental setup is shown in FIGURE 4 where two of our SRRs (Sample Return Rover) have been retrofitted with gimbals to carry a load. We demonstrated under closed loop control the second step of the 4 step deployment scenario shown in FIGURE 2 in the Arroyo Seco at JPL in September of 2000. A number of coordinated motion behaviors are required for transport of an extended container using the sequence illustrated in FIGURE 5. The four phases are: (1) clear the CSU in preparation for a turn, (2) traverse to a staging area, (3) survey the deployment area for a clear site, (4) traverse to docking site. The two main behaviors required for these four phases are *Assume Transport Formation*, a group behavior that autonomously guides the two rovers into a specific formation such as row (side-by-side) or column (leader-follower) as shown in FIGURE 4, and *Coordinated Transport*, a group behavior that autonomously controls the system during any traversal.

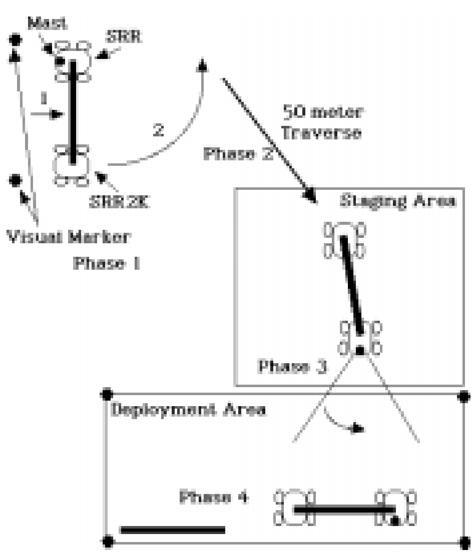



FIGURE 5. Four Phase Sequence for Transport of an Extended Container by Two Rovers. See Text for Details.

Both of these group behaviors rely on compliant control of the extended container so as not to drop it during the movement. Minimizing the communication between rovers is also a goal, since there are power and bandwidth restrictions for systems deployed on planetary surfaces such as Mars. The gimbal shown in the middle of FIGURE 4 has 6 DOF force/torque sensors and pots. Monitoring of the pot settings is used for control of the angular offset between the rovers, and monitoring of the force sensors is used for side-slip and terrain offsets between the rovers. *Comply* is a group behavior that uses communication between the rovers only at the beginning of a sequence and when there is a need to stop in order to re-center the load.

Our experimental runs in the Arroyo Seco at JPL were used to determine the number of actuators that will be needed for robust control of the transport sequence. Since the gimbals were not actuated, all repositioning of the container had to be done using the robots. This is potentially a problem on slopes of more than 10°, where the load will tend to shift backwards onto the follower robot. A row formation can be used to partially offset this shift, but obstacle detection in this formation is more complicated. Actuation of the gripper mechanism is the best compromise, in that it allows a grip/re-grip process to be used to keep the load balanced. Our collaborators in this research at NASA Johnson are studying gripper designs and control strategies using an emulation of the dual robot motion based on internal state information from our field tests.

## CONCLUSIONS

A manned habitat on Mars is a NASA mission being considered for the second decade of the next century. This paper has examined some of the necessary robotics requirements for precursor missions within the next ten years. Current control, strength, and survivability of NASA planetary rovers precludes their use for such missions. On the control issue, we have described recent work at JPL in the area of behavior-based systems. In particular, the use of CAMPOUT for power system deployment operations was described.

## ACKNOWLEDGMENTS

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